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Do Swimmers Conform to Criterion Speed during Pace-Controlled Swimming in a 25 m pool using a visual light pacer?

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Do swimmers conform to criterion pace during pace-controlled swimming in a 25 m pool using a visual light pacer?

Abstract: The purpose of this study was to investigate whether swimmers follow accurately the instructed speed (v_{target}) with the aid of a commercial visual light pacer during front crawl and backstroke swimming in a 25 m pool. Ten male swimmers performed 50 m front crawl and backstroke at different speeds (controlled by a visual light pacer) in a 25 m pool. The mean speed during the 50 m swimming (v_S) was quantified from the time measured by a stopwatch. The mean speed of the centre of mass during a stroke cycle in the middle of the pool (v_{COM}) was calculated from three-dimensional coordinates obtained from Direct Linear Transformation of two-dimensional digitised coordinates of 19 segment endpoints for each of six cameras. Swimmers achieved accurate v_S in front crawl and backstroke (ICC = 0.972 and 0.978, respectively). However, v_{COM} for the single mid-pool sample had lower correlations with v_{target} (ICC = 0.781 and 0.681, respectively). In backstroke, v_{COM} was slower by 4.1–5.1% than v_{target}. However, this was not the case in front crawl (1.0-2.7%). With the use of a visual light pacer, swimmers can achieve accurate mean speed overall but are less able to achieve the target speed stroke by stroke. (200 words)

Keywords: swimming, pacing, visual light pacer, front crawl, backstroke,

Introduction

Swimming is mechanically inefficient, and a poor pacing strategy will increase the rate of fatigue (Thompson, 2014). For example, a frequent change of pacing during swimming means that the swimmer would often have to decelerate and accelerate his/her body in the water. This strategy is inefficient from a physiological perspective because when a swimmer accelerates the body, the swimmer accelerates not only the body mass but also a corresponding added mass of the water, which requires extra energy being expended (Vilas-Boas, Fernandes, & Barbosa, 2011). Therefore, maintaining a constant speed is a physiologically efficient strategy in swimming.

For this reason, different methods to control the pace have been established in swimming research and/or testing such as the use of the flume (Tomikawa, Shimoyama, & Nomura, 2008) or sound based and visual light pacer (Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes, 2011; Thompson, MacLaren, Lees, & Atkinson, 2002). Among those pacing tools, visual light pacers have been widely used for controlling the speed of the swimmer in many studies (e.g. Figueiredo, Toussaint, Vilas-Boas, & Fernandes, 2013; Laffite et al., 2004; and Reis et al., 2010).

A light pacer has an advantage that one can use it in a free-swimming condition and it gives a swimmer a direct instruction unlike a flume and a sound-based pacer. Several commercial light pacers are used in the literature, such as TAR. 1.1 (GBK-electronics, Aveiro, Portugal), Pacer 2 (GBK-Electronics, Aveiro, Portugal), and Arcom PCO24 (Arcom Control Systems, Kansas City, US). Those pacers consist of LED lights set on the pool floor in line with the swimming direction with a 1 m (or more) interval between each light. The lights flash consecutively along with a pre-programmed speed that informs a swimmer the speed he/she is required to follow.

Even though visual light pacers have been frequently used in swimming, there have only been a small number of studies in which the ability of swimmers to conform consistently to a criterion pace in a condition of training or competition (e.g. 25 m pool) is discussed. It has been reported that there are high intraclass correlation coefficients (ICC) of 0.973 – 0.996 between the instructed and swimming speed in a series of 100 m front crawl trials with the use of a light pacer (Keskinen, 1997). However, the results were based on mean speeds of whole 100 m trials and those between the 5 m and the 45 m point of a 50 m pool during the trials. Therefore, it is unclear whether the swimmers successfully followed the instructed speed (v_{target}) throughout the trial.

It has been reported that the mean speed in turn phase (from the last hand-entry before the turning motion to the head breaking out the water surface) is faster than that during free swimming phase by approximately 10% (Veiga, Cala, Mallo, & Navarro, 2013). It has also been shown that the swimming speed decreases from pushing off the wall to free swimming by 43.5% (Takeda, Ichikawa, Takagi, & Tsubakimoto, 2009). Assuming that swimmers try to control their overall mean speed during the swimming trial (v_S) when using a light pacer, it is possible that swimmers achieve slower speeds than v_{target} in the middle of the pool to offset the fast speed achieved after the push off. In the aforementioned study by Keskinen (1997), data from the first and last 5 m were removed from the calculations. However, it is unclear to what extent this strategy excludes the effect of push-off and subsequent underwater kicking on the calculated swimming speed.

Swimmers may also struggle with aligning a specific point of the body (e.g. head) with the illuminating light (Thompson et al., 2002). This concern is reasonable considering that the speed of a swimmer is generally not constant but fluctuating during a stroke cycle (Figueiredo, Kjendlie, Vilas-Boas, & Fernandes, 2012;

Psycharakis, Naemi, Connaboy, McCabe, & Sanders, 2010). Therefore, it is important to compare v_{target} with speed swimmers achieve in the mid-pool (e.g. the mean speed during a stroke cycle in the mid-pool) to investigate the ability of swimmers to conform consistently to a criterion pace.

Another concern about available commercial pacers is that many of them have the lights with the interval between each light of 1 m or more. Stroke frequency (SF: the number of strokes a swimmer achieves in a given time) of elite swimmers in their sprint pace is approximately 55 cycles/min with their swimming speed being around 1.80 m/s (McCabe, Psycharakis, & Sanders, 2011). A light pacer with a 1 m distance between each light would flash the light with a time interval of 0.56 s. Given that SF of 55 cycles/min corresponds to stroke cycle time of 1.09 s, a swimmer would get the speed instruction by the lights only once or maximum twice during a stroke cycle, which would potentially make the swimmer follow the criterion speed difficult in some stroke cycles.

To investigate the mean speed during a stroke cycle, the mean speed of the centre of mass (v_{COM}) or a single point (such as the hip joint) are often used (Deschodt, Arsac, & Rouard, 1999; Figueiredo, Vilas-Boas, Maia, Gonçalves, & Fernandes, 2009; McCabe et al., 2011; Psycharakis et al., 2010). Theoretically, both v_{COM} and velocity of a single joint should produce accurate mean velocity during a stroke cycle if the swimmer presents the identical posture at the start and the end point of the cycle.

However, this also implies that the result would be greatly affected by a digitising error in the joint displacement of the start/end points of the analysed cycle. On the other hand, v_{COM} calculation includes the displacement of multiple joints, and a digitising error in a joint would potentially offset (if not all) the error in other joints since the digitising error is a random error rather than a systematic one, which suggests that the use of v_{COM} is probably preferable to hip (or another fixed point) velocity when assessing the speed of swimmers to minimise the risk due to a digitising error.

Although v_{COM} in swimming has been investigated with v_{target} being provided by the use of a light pacer (e.g. Figueiredo et al., 2011), there have been no investigations to assess the ability of swimmers matching v_{COM} to v_{target}. Given that there are concerns above due to turns and specification of commercial light pacers, it is possible that swimmers do not necessarily present an accurate mid-pool v_{COM}, especially in a 25 m pool where push-off has a greater impact on swimming performance than in a 50 m pool.

Furthermore, there is a paucity of information on the pacing accuracy when setting the light pacer overwater for backstroke pacing (setting a pacer on a wire instead of placing it on the floor). Establishing detailed information on accuracy and potential limitations of using a light pacer would be beneficial for coaches and researchers to improve the precision of training and testing of swimmers. Therefore, the purpose of this study was to compare v_{target} and v_{COM} as well as v_S to investigate whether the use of a commercial visual light pacer is an accurate method to control the speed of swimmers during front crawl and backstroke. Assuming that swimmers would try to match a total time to the instructed one (i.e. matching v_S to v_{target}), we hypothesised that a) the use of a commercial light pacer in a 25 m pool would cause a systematic error (i.e. slower v_{COM} than v_{target}) due to the push-off velocity being faster than free-swimming velocity, and b) v_{COM} would also have a relatively larger random error than v_S because of the speed instructing by a light pacer not being constant.

Methods

Participants

Ten male competitive swimmers (age 17.47 ± 1.00 years; height 179.14 ± 5.43 cm; body mass 69.94 ± 6.54 kg) participated in this study. Mean respective 100 m front crawl and backstroke best records of the participants were 54.50 ± 1.23 and 60.56 ± 1.29 s, which corresponded to 82.49 ± 1.91 and 80.85 ± 1.72% of the world records. The purpose, procedure, and potential risks of this study were reviewed and approved by the ethics committee of the university based on the British Association of Sport and Exercise Sciences guidelines. The reviewed information was provided to the participants both verbally and in writing, and written informed consent was obtained from each participant.

Testing Protocol

Prior to testing, participants were marked on 19 anatomical landmarks using black oil and wax-based cream (Grimas Créme Make Up). The marked anatomical landmarks were: the vertex of the head, acromioclavicular joint, greater tubercle of the humerus (shoulder), olecranon process of ulna (elbow), wrist axis, 3rd distal phalanx (finger), greater trochanter (hip), patella axis (knee), lateral malleolus (ankle), 5th metatarsophalangeal joint, and 1st interphalangeal joint (toe). For the marking on the vertex of the head, a pre-marked white swim cap was used. Each participant was captured by digital cameras from front and side view simultaneously to obtain personalised body segment parameter (BSP) data of the participants using the elliptical zone method (Jensen, 1978).

The testing was conducted in a centre lane of a 25 m indoor pool with 1.9 m depth. The testing lane was calibrated before the testing sessions using an orthogonal calibration frame (De Jesus et al., 2015) with dimensions of 6 m length aligned with the swimming direction (X), 2.5 m height (Y), and 2 m width (Z). The total calibrated volume incorporated 30 m^3, and 64 control points (32 underwater, and 32 above the water control points) were used for subsequent three-dimensional direct linear transformation (3D-DLT). A spirit was attached on the calibration frame to ensure the X-Z plane being the same plane as the water surface.

The testing session consisted of 3 × 50 m swims at different swimming speeds and was conducted for both front crawl and backstroke with at least 24 h rest between them (three trials per each technique). Testing speeds for both techniques were approximately 93, 88, and 82% of their maximum effort speed (calculated using a mid-pool v_{COM} during 50 m maximum effort swimming) in each technique (Slow, Moderate, and Fast, respectively), which was individually determined by a pilot study. The order of the 3 × 50 m test was randomised to minimise potential errors due to fatigue, and four minutes recovery time was provided after every 50 m swim.

The testing speeds were controlled by a visual light pacer (Pacer2, GBK-Electronics, Aveiro, Portugal) that was a 25 m long cable device equipped with 26 LED lights for each metre from 0 to 25 m points. The LED lights flashed consecutively to indicate the pace the swimmer had to maintain to match the pre-programmed speed. The pacer was positioned on the bottom of the pool for front crawl trials and approximately 2 m above the water surface with stainless steel wire for backstroke trials. The final time of each 50 m was manually recorded by a stopwatch (SVAS003, SEIKO, Tokyo, Japan) operated by the same investigator throughout the trials. The time of the 50 m was recorded from the instant of the initial push-off until the swimmer touches the wall when completing the 50 m swimming.

Swimmers were instructed to swim at speed such that the light illuminated when their head was directly above (or under) it. The light pacer was programmed to flash the lights at a constant speed, meaning that swimmers would have to keep constant speed for the whole 50 m to follow the pace accurately. Swimmers were instructed to avoid tumble turns (i.e. they conducted open turns) and underwater kicking after the start and turn, as it is often the case in studies that employ a light pacer (e.g. Figueiredo et al., 2011), in order to assess the accuracy at the condition with which the pacer is frequently used. Before the 3 × 50 m tests, swimmers participated in an individual warm-up that included familiarisation for the apparatus. During this familiarisation period, the swimmers also practised open turns with the light so that speed variability during the testing due to the turning technique would be minimised.

Data Collection

To obtain kinematics in front crawl and backstroke using a 3D-DLT method during each 50 m trial, the calibrated space in the pool was captured by six high definition cameras (four underwater and two above the water, Sony, HDR-CX160E, Tokyo, Japan, sampling rate: 50 fps, shutter speed: 1/120 seconds, movie resolution: 1920×1080/50p) synchronised using a LED system. Waterproof camera cases (Sony, SPK-CXB, Tokyo, Japan) were used for the underwater cameras.

All cameras were fixed at different heights and angles to the line of motion of the swimmer to avoid the camera axes being in the same plane to maximise the accuracy of the DLT calculations. The angle between the optical axes of the two above water cameras was approximately 100º, while those of the four underwater cameras were 75-110º. Swimmers were instructed to swim directly above the lane-line in front crawl and under the stainless wire in backstroke through the centre of the calibrated space. Videos which captured the calibrated space in the latter 25 of each 50 m were used for the analysis, which was based on the perspective that swimmers would be more familiarised with v_{target} in the second 25 m than the first one. The setting for the cameras and calibration frame is shown in Figure 1. Swimmers were instructed not to breath when swimming in the calibrated area in front crawl since breathing motion affects upper limbs kinematics and v_{COM} of the swimmer (McCabe, Sanders, & Psycharakis, 2015).

Figure 1 near here

Data Processing and Analysis

To calculate personalised BSP data, the elliptical zone method (Jensen & Bellow, 1976) was applied using the ‘E-Zone’ software (Deffeyes & Sanders, 2005). In this method, the body is assumed to consist of 16 segments: head, neck, thorax, abdomen, upper arms, forearms, hands, thighs, shanks, and feet. Each segment is reconstructed with a series of elliptical cylinders based on the outline of each segment that is obtained my manual digitising using frontal and side view photos of the participants with an anatomical position. For each elliptical cylinder, the volume, mass, location of COM, and moments of inertia are calculated by the standard formulas presented by Jensen (1978) using segment density data of Dempster (1955).

Video files of calibration and the testing session were transferred into a computer. All six camera views were checked to ensure that the whole body of the swimmer was in the calibrated space during the selected stroke cycle. The video files were trimmed in Ariel Performance Analysis System software (Ariel Dynamics, Inc, CA), and the same software was used to digitise and calculate 3D coordinates. To obtain one complete stroke cycle, the start and the end points of the stroke cycle were defined as the entry of the wrist marker into the water and the next entry of the same wrist, respectively. The digitising operator used the skin-painted markers as a guide and predicted the location of anatomical landmarks in each video field so that the digitised point would represent the centre of the joint of the swimmers rather than the location of the markers. The operator had a total of nine years of degree and postgraduate level education in sports and exercise sciences and was assumed to have sufficient knowledge of the musculoskeletal system.

Five extra points before and after the stroke cycle were included in the trimmed video files to minimise errors at the end of the data sets associated with filtering and derivation of velocity data. A 4th order Butterworth filter with a 4 Hz cut-off frequency was applied after extrapolating the data by reflection to an additional 20 points beyond the start and finish of the stroke cycle (in total, 25 points of additional data at each end) as added insurance against distortion of the endpoints of the data set. The rationale for choosing 4 Hz as the cut-off was based on the Fourier spectral analysis indicating that little power (<1%) was contained in frequencies greater than 4 Hz.

The digitising process was conducted at a frequency of 25 Hz that was chosen based on the following rationales: (i) the appropriate sampling frequency in motion analysis is 8-10 times higher than the highest frequency present in the digitised activity (Challis, Bartlett, & Yeadon, 1997); (ii) in front crawl, the highest frequency is likely produced by the kick motion, which is a roll motion with three maxima and three minima (Sanders & Psycharakis, 2009); (iii) the stroke frequency in sprint front crawl is approximately 55 cycles/min (McCabe et al., 2011). These shreds of evidence mean that the time taken for one stroke cycle in sprint front crawl is 1.09 s, and the highest frequency present in front crawl is 2.75 Hz, therefore, the appropriate sampling frequency would be 22.0 – 27.5 Hz.

Given that front crawl and backstroke have similar motion characteristics and the stroke frequency in backstroke is lower than that in front crawl (Chollet, Chalies,

& Chatard, 2000; Chollet, Seifert, & Carter, 2008; Hellard et al., 2008), digitising at 25 Hz is fast enough for both swimming techniques. One trial for each swimming technique was digitised five times by the same researcher to assess the digitising reliability at 25 Hz.

Calculated variables

In the present study, v_{target} that is used for data analysis was the speed programmed in the pacer before the testing by an operator. COM location was determined by summing the moments of the segment COM mass about the X, Y, and Z reference axes, and v_{COM} was obtained by differentiating the X displacement of COM over the whole stroke cycle with respect to time taken for the cycle (mean COM velocity in the stroke cycle). v_S during each 50 m trial was obtained by the final time of each 50 m timed by the stopwatch (v_S = 50/f*inal time*). SF (Hz) of each swimmer at each intensity in both techniques was acquired as the inverse of a stroke cycle time of the analysed stroke. Absolute errors of v_{COM} (AEv_{COM}) and v_S (AEv_S) were calculated by subtracting v_{COM} and v_S from v_{target}, and relative errors of v_{COM} (REv_{COM}) and v_S (REv_S) were obtained by dividing AEv_{COM} and AEv_S by v_{target} and multiplying by 100 to express as a percentage.

Statistical analysis

Digitising reliability for v_{COM} was assessed by 95% confidence intervals (CI) as well as the coefficient of variation (CV) of v_{COM} in the five repeated trials.

To investigate the pacing ability of the swimmers, ICC with two-way random single measures model between v_{target} and v_{COM}, and between v_{target} and v_S were obtained. To assess the significance of the differences between v_{target}, v_{COM}, and v_S and its relationship with the swimming intensity, two-way repeated measures ANOVAs were used (intensities × velocity variables). Even though three velocity variables (v_{target}, v_{COM}, and v_S) were obtained in this study, only two velocity variables were used in one ANOVA (v_{target} and v_{COM}, and v_{target} and v_S, respectively) since the difference between v_{COM} and v_S was not an important factor to achieve the aim of the current study. The assumption of sphericity was tested using the Mauchly's test of sphericity. Since this assumption was not violated, no further data adjustments were conducted.

When a significant main effect was found between variables, a student's t-test was used to determine which intensities the main effect was attributed to, with a calculation of Cohen's d as effect size evaluation. The normality of distribution for all data was checked using Shapiro-Wilk test and confirmed. Statistical significance was set at $p < 0.05$, and the statistical tests were conducted using IBM SPSS Statistics 19 (IBM Corporation, Somers, NY, USA).

Results

In both front crawl and backstroke, CV in the test-retest reliability for obtaining v_{COM} was within 1% (0.538 and 0.315% in front crawl and backstroke, respectively) with 95% CI being 1.645-1.667 and 1.528-1.540 m/s in front crawl and backstroke, respectively (Table 1).

When comparing v_{target} and v_S, no main effect of the variable was found in both front crawl and backstroke (Table 2). There was no main effect of the variable when the ANOVA was conducted between v_{target} and v_{COM} in front crawl, while a significant main effect was detected in backstroke (Table 2; $F=10.69$, $p<0.05$). There was no interaction between the variables and testing intensity (Slow, Medium, and Fast). v_{COM} was slower than v_{target} in every trial in backstroke (Table 3; Slow: $p<0.05$, $t=2.54$, $d=0.704$; Moderate: $p<0.05$, $t=2.44$, $d=0.724$; Fast: $p<0.01$, $t=3.69$, $d=0.86$).

Table 1 near here

Table 2 near here

Mean SF of the swimmers at Slow, Moderate, and Fast intensity trials were 0.57, 0.66, and 0.73 Hz in front crawl and 0.50, 0.54, and 0.63 in backstroke, respectively (Table 3). In both front crawl and backstroke, mean REv_{COM} and REv_S were less than 5% except REv_{COM} at Fast trial in backstroke where REv_{COM} was 5.17% (Table 4).

Table 3 near hear

Table 4 near here

ICC between v_{target} and v_S as well as those between v_{target} and v_{COM} in front crawl and backstroke are shown in Figure 2. In both swimming techniques, ICC between v_{target} and v_S (ICC = 0.972 and 0.978 in front crawl and backstroke, respectively) were higher than those between v_{target} and v_{COM} (ICC = 0.781 in front crawl and ICC = 0.681 in backstroke). 95% confidence intervals in ICC between v_{target} and v_{COM} varied in both techniques, especially in backstroke (0.582- 0.890 and 0.130- 0.873 in front crawl and backstroke, respectively).

Figure 2 near here

Discussion and Implications

The results from digitising reliability indicate that any differences (relating to v_{COM}) within 0.52 and 0.32% or 0.2 and 0.1 m/s in front crawl and backstroke, respectively, could be due to a digitising error.

There was a significant main effect between v_{COM} and v_{target} in backstroke with v_{COM} was being slower (by 4.52, 4.14, and 5.11% at Slow, Moderate, and Fast trials, respectively) than v_{target}. On the other hand, there were no differences between v_{COM} and v_{target} in front crawl trials. These results indicated that REv_{COM} and AEv_{COM} in backstroke contained a systematic error, which caused slower v_{COM}

than v_{target}, and those variables in front crawl contained only random errors. In other words, the present study demonstrated that the use of the pacer does not cause any systematic error (due to the turning technique) at least in front crawl swimming with open turn techniques, against our first hypothesis.

In this study, tumble turns and underwater kicking after the turns were restricted and swimmers conducted open turns in both techniques. However, open turn techniques differed among the techniques due to the difference in the body posture between the techniques, i.e. swimmers touched and pushed off the wall with their face down in front crawl but did those motions with their face up in backstroke. Perhaps conducting the different open turn techniques affected the push-off speed after the turn that potentially influenced the difference in the result between the techniques. Nevertheless, no investigation was conducted around the turn in this study, and further studies are necessary to assess the effect of the turning techniques on the speed of swimmers.

Another possibility of a reason of the systematic error in backstroke was the setting of the pacer. In backstroke, the light pacer was attached on a wire above the swimming lane. Even though the wire was tightened, it is possible that there was slight slack on the wire due to the gravity (especially around the centre of the pool where the swimming motion was recorded) since only the ends of the wire were fixed on the wall – which might have shortened the horizontal distance between each light relative to the surface of the pool in the middle of the pool.

The results of high ICC between v_{target} and v_S (0.972) and small REv_S in front crawl and backstroke support the result of Keskinen (1997) in which high ICC between v_{target} and mean speed of 100 m front crawl was reported (ICC=0.996). These results also supported our initial assumption – swimmers tried to match their overall time to that instructed by the pacer. On the other hand, ICC between v_{target} and v_{COM} showed slightly lower ICC values in front crawl and backstroke (ICC = 0.781 and 0.681, respectively), and consequently, REv_{COM} and AEv_{COM} tended to be larger than the errors in v_S. These results implied that even though the swimmers controlled their v_S accurately, it does not necessarily mean that they control v_{COM} with a comparable accuracy, which supported our second hypothesis.

Despite the lower accuracy in controlling v_{COM} compared with v_S, it should be noted that REv_{COM} in front crawl and backstroke were less than 5%, except backstroke Fast trials. In gait studies, target speed ± 5% is often considered to be acceptable when controlling the speed (Gard, Miff, & Kuo, 2004; Michaud, Gard, & Childress, 2000; Pohl, Messenger, & Buckley, 2007). If the same standard is applied for swimming research, one can consider that the use of the light pacer is sufficient to control v_{COM}. Nevertheless, in swimming, the effect of speed variation is probably more crucial than gait, since the acceleration of the body would have a large impact on the energy expenditure of the swimmer due to the drag and added mass. Therefore, researchers and coaches should be aware of the magnitude of error in v_{COM} with respect to v_{target} and consider if the use of a light pacer would suit their aim.

Probably the smaller ICC between v_{target} and v_{COM} than between v_{target} and v_S was partly due to the design of the pacer. In the present study, LED lights on the device are separated by 1 m and the lights flash intermittently. Even though this type of the pacer (with flashing lights have 1 m or more distance between them) has been widely used in swimming research (Aspenes et al., 2009; Figueiredo, Barbosa, Vilas-Boas, & Fernandes, 2012; Gonjo et al., 2018; Kjendlie, Ingjer, Madsen, Stallman, & Stray-Gundersen, 2004; Marinho et al., 2004), intermittent flashing means that swimmers are not informed of the required speed constantly by the system.

To control the speed during each stroke cycle with intermittent flashing lights, swimmers first have to observe the flashing light, then predict the required speed that allows their head being in alignment for the next light, and adjust their speed. The smaller ICC between v_{COM} and v_{target} as well as the large REv_{COM} probably reflected the error adjustment of swimmers (i.e. when they were behind the flashing light, they accelerated their body whereas they decelerated it when they were ahead of the light). This hypothesis is in line with the suggestion that locating a specific point of the body constantly in relation to an illuminating light in the water is difficult (Thompson, 2014; Thompson et al., 2002). However, there was no direct evidence from the present study that supported this hypothesis. Therefore, the effect of using the light pacer on variability for v_{COM} of swimmers among several stroke cycles should be further investigated.

The interval between each light (1 m) of the device has another issue which potentially caused the error in matching v_{COM} to v_{target}. In the current study, swimmers had SF of 0.57-0.73 and 0.50-0.63 Hz (comparable to stroke cycle time of 1.75-1.37 s and 2.00-1.59 s) with v_{COM} being 1.43-1.65 and 1.25-1.41 m/s in front crawl and backstroke, respectively. At corresponding trials, v_{target} in front crawl and backstroke were 1.44-1.65 m/s and 1.30-1.49 m/s. This means that lights of the pacer were flashed with an interval of 0.69-0.60 and 0.80-0.71 s depending on the intensity in front crawl and backstroke, respectively. These results imply that swimmers could see the flashing light twice in one stroke cycle. Given that one stroke consists of two arm motions (left and right), swimmers were likely informed the pace by the light only once per each arm motion. In this case, it was probably difficult for swimmers to adjust the upper limb motion so that v_{COM} matching v_{target} stroke by stroke. Perhaps shorter interval (0.5 m or less) between the lights would be suitable for a visual light pacer so that coaches and researchers can inform the pace to swimmers more accurately.

Conclusion

Overall, in a 25 m pool, a visual light pacer (with the light interval of 1 m) is an accurate device to control 50 m time of swimmers, but coaches and researchers should consider that they would encounter with up to 2.8 and 5.2 % error in front crawl and backstroke when their interest is controlling v_{COM}.

Disclosure statement

The authors declare no conflicts of interest.

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Table 1. Digitising reliability for obtaining the centre of mass speed in front crawl and backstroke.

Techniques	Mean (m/s)	SD (m/s)	CV (%)	95% CI (m/s)	
				Lower	Upper
Front Crawl	1.656	0.009	0.518	1.645	1.667
Backstroke	1.534	0.005	0.315	1.528	1.540

SD (Standard deviation); CV (Coefficient of variation); CI (Confidence Intervals)

Table 2. Instructed speeds, mean centre of mass speeds during a stroke cycle, and mean speeds during the 50 m trials in front crawl and backstroke.

Compared variables	Technique	F-value	p-value	η_p^2	Interaction with testing intensity
v_{target} vs v_{COM}	Front Crawl	1.855	0.206	0.171	n.s.
	Backstroke	10.689	<0.05	0.543	n.s.
v_{target} vs v_S	Front Crawl	2.177	0.174	0.195	n.s.
	Backstroke	0.012	0.916	0.001	n.s.

v_{target} (instructed speed); v_{COM} (mean centre of mass speed over the period of whole stroke cycle); v_S (mean speed in the whole trial)

Table 3. Instructed speed, Centre of mass velocity during one stroke cycle, the mean velocity during 50 m trials.

Variables	Front Crawl			Backstroke		
	Slow	Moderate	Fast	Slow	Moderate	Fast
v_{target} (m/s)	1.44±0.07	1.55±0.07	1.65±0.07	1.30±0.06	1.40±0.07	1.49±0.07
v_{COM} (m/s)	1.43±0.126	1.52±0.13	1.60±0.14	1.25±0.10*	1.34±0.09*	1.41±0.10**
v_S (m/s)	1.44±0.08	1.56±0.08	1.67±0.08	1.30±0.07	1.41±0.06	1.48±0.07
SF (Hz)	0.57±0.08	0.66±0.12	0.73±0.15	0.50±0.07	0.54±0.06	0.63±0.09

v_{target} (instructed speed); v_{COM} (mean centre of mass speed over the period of whole stroke cycle); v_S (mean speed in the whole trial); SF (Stroke Frequency); * (significant difference from v_{target} [$p<0.05$]); ** (significant difference from v_{target} [$p<0.01$]

Table 4. Absolute and relative errors in centre of mass velocity during a stroke cycle and the mean velocity during 50 m trials relative to the instructed speed

Variable	Technique	Absolute error (m/s)			Relative error (%)		
		Slow	Medium	Fast	Slow	Medium	Fast
v_{COM}	Front Crawl	0.01	0.03	0.04	1.13	2.23	2.80
	Backstroke	0.06	0.06	0.08	4.57	4.13	5.17
v_S	Front Crawl	0.00	-0.01	-0.02	0.14	-0.32	-1.29
	Backstroke	0.00	0.00	0.00	0.27	-0.29	0.23

v_{target} (instructed speed); v_{COM} (mean centre of mass speed over the period of whole stroke cycle); v_S (mean speed in the whole trial)

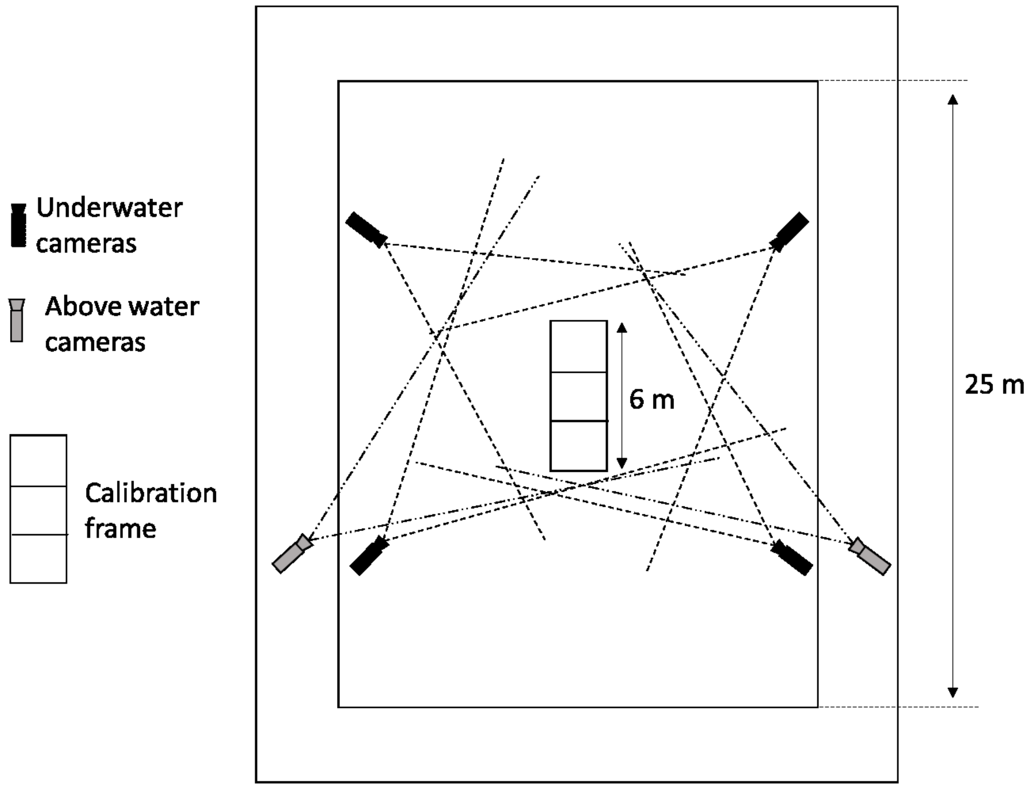
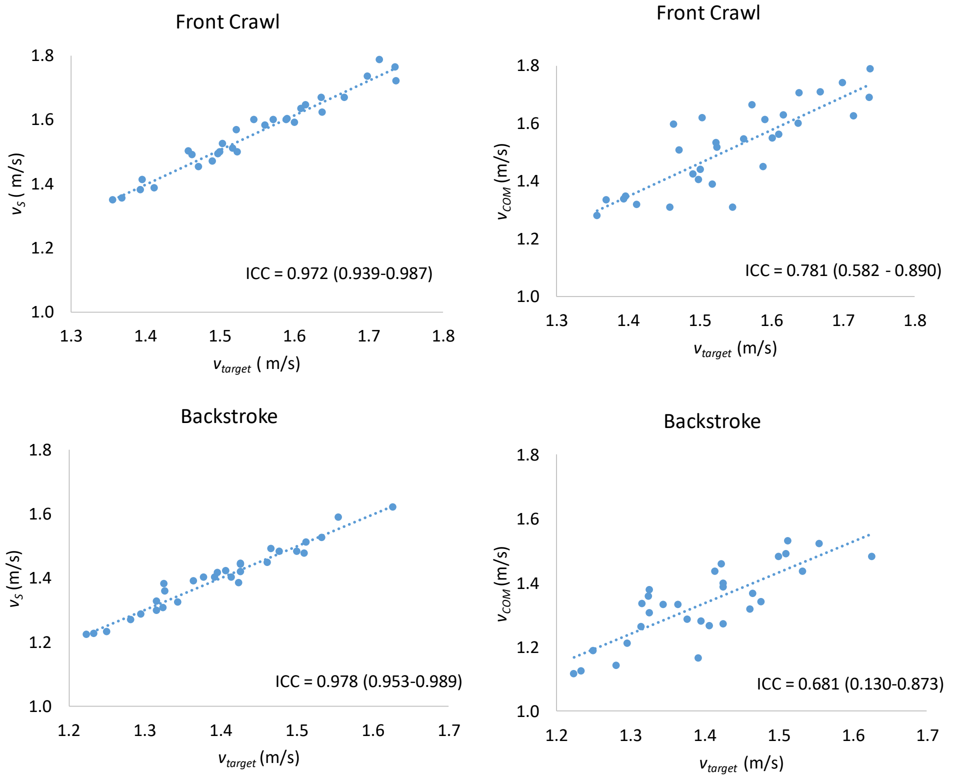


Figure 1. Diagram of the setting of the cameras and calibration frame.



v_{target} (instructed speed); v_{COM} (mean centre of mass speed over the period of whole stroke cycle); v_S (mean speed in the whole trial)

Figure 2. Intraclass correlation coefficient (ICC) between the instructed speed and mean speed during the 50 m trials and between the instructed speed and centre of mass speed in front crawl and backstroke.